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AVHRR/2

ADVANCED VERY HIGH RESOLUTION RADIOMETER

TECHNICAL DESCRIPTION

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7.0 CALIBRATION

7.1 Thermal Channels Calibration

The infrared calibration signal to the AVHRR is the difference in signals from a calibration blackbody of known temperature and a blackbody of essentially zero exitance. The zero level source is provided by deep space during in-flight calibration and by a liquid nitrogen cooled black cavity during chamber calibration. Other calibration requirements are listed in Table 7.1-1. We have interpreted the temperature calibration accuracy of the chamber targets (B.b.) to mean the equivalent temperature accuracy determined by all error sources.

7.1.1 Calibration Accuracy

The absolute radiometric calibration of the instrument is to have an accuracy of $\pm$ 0.5K throughout the calibration range of each channel. Before we consider how this requirement can be met, let's define some terms. In particular, we can differentiate between precision (or sensitivity) and accuracy by means of the following:

Precison: A measurement is regarded as precise if the dispersion of values, i.e., the standard deviation σ, is small.

Accuracy: A measurement is regarded as accurate if the values cluster closely about the correct value.

By accuracy of an individual measurement or of an average of measurements is usually meant the maximum possible error (constant and/or random) that could influence the observed value. It is frequently thought of in terms of the number of significant figures to which a value can be regarded as correct.

The precision is limited by the instrument noise, i.e., by the sensitivity. In order to measure the noise of the instrument and to reduce its effect on the absolute radiometric calibration, a set of n measurements are made at each calibration point. The

TABLE 7.1-1 Requirements for Thermal Channels Calibration

A. Inflight Blackbody

a. Measured with platinum resistance thermometers appropriately arrayed to adequately define the temperature.

b. Temperature sensor instrumentation accuracy of ±0.1K.

c. To be compared with the chamber targets during thermal vacuum calibrations.

B. Chamber (Standard) Blackbodies

a. Greater emissivity, temperature stability, and temperature sensor accuracy than inflight target.

b. Absolute temperature measurement accurate to ±0.5K.

precison (or sensitivity is then given by the best estimate of the standard deviation (see for example, D. C. Baird, Experimentation: An Introduction to Measurement Theory and Experiment Design, Prentice - Hall, 1962).

$$\sigma = [\Sigma \, (x - \bar{x})^2/(n - 1)]^{\frac{1}{2}},$$

where x is an individual measurement and $\bar{x}$ the average of n measurements. On the other hand, the standard deviation of the average of n measurements is given by

$$\sigma_n = \sigma/n^{\frac{1}{2}}.$$

The influence of the instrument noise and of all other random errors can therefore be reduced to the point where the accuracy of a calibration is determined by the systematic errors in the calibration target itself. This could be done during both the chamber (Section 7.1.2) and in-flight (Section 7.1.3) calibration. There are 10 calibration points (elemental dwell times) during each scan of a target, and so for a 1 minute period, we have n = 3600.

Before we consider the errors in the calibration targets, however, let's list all the components and procedures that can limit the accuracy of a calibration. We can identify two major areas, within which there may be important subareas. They are as follows:

A. Calibration target
   a. Temperature: Measurement { Sensor / Instrumentation
      Gradients or uniformity
      Control (chamber)
   b. Non-blackenss
B. Electronics
   a. Noise (NEΔT)
   b. Signal processing: Digitization
      Recording
      Transmission (In-flight)
      Ground Processing

We will limit ourselves to errors from sources A and B.a. We are therefore assuming that the experiment is so designed that the errors contributed by B.b. are negligible by comparison.

If the difference in surround between chamber targets can be made zero or very small, the non-blackness errors will be greatly reduced and the accuracy of the calibration limited only by the errors and uncertainties in the calibration target temperature. Accuracy estimates for the chamber calibration are given in Table 7.1-2 and for the in-flight calibration in Table 7.1-3.

We see that we have met our objective of 0.5K for the total channel calibration error throughout the temperature range of both channels.* In addition, the total in-flight error at 295K has a comparable value when the calibration is made in the absence of direct sunlight (See Section 3.11). In the following sections, we consider in detail how we obtained the estimates listed in Tables 7.1-2 and 7.1-3.

7.1.2 Chamber Calibration Targets

Errors and uncertainties in the exitance (emitted Wcm^{-2}) of the calibration target arise from its temperature inaccuracies (Section 7.1.2.1) and its deviation from blackness (Section 7.1.2.2). Because a calibration signal is equal to the difference in signals from a calibration target and a cold space target, the inaccuracy from non-blackness is greatly reduced by making the two targets the same form and exposing them to the same surround.

7.1.2.1 Temperature Uncertainty

The accuracy of the calibration target temperature is limited by measurement errors, control stability, and gradients. The uncertainty in a temperature measurement relative to the international practical temperature scale (IPTS-68, which is essentially

* We have arbitrarily set the lower limit in Channel 4 at 250K, where the noise equivalent temperature difference is approximately 1K. Calibration accuracy for Channel 5 would be approximately the same as for Channel 3.

Table 7.1-2 Accuracy of Chamber Calibration

Temperature:		
Measurement	Sensor	±0.05K
	Instrumentation	±0.05
	Control	±0.05
Gradients' base (uniformity)		±0.10*
	Honeycomb (1K)*	±0.06
	Wall: Diff from box (±1K)*	±0.0026
	Wall: Gradient within (5K)*	±0.00045
Accuracy (max of errors + uncertainties)		0.32K

Non-blackness

Net from standard-cold space difference

(10K difference in surrounds):

Channel	T	$\delta^2 T$
3	185K	+0.018K
3	320	-0.046
4	250	+0.027
4	320	-0.016

Total accuracy (including noise for n = 3600)**

Channel	T	δ T
3	185K	0.35K
3	320	0.37
4	250	0.37
4	320	0.34

* Actual value of gradient.

** Based on specified NETD of 0.12K at 300K.

Table 7.1-3 Accuracy of In-flight Calibration For T = 295K *

Temperature:

Measurement	Sensor	±0.05K
	Instrumentation	±0.10
Gradients	Base	±0.08
	Honeycomb (1K)	±0.08
		±0.31

Non-blackness:

Channel	δ T
3	-0.080
4	-0.029

Total accuracy (including noise for n = 3600)

Channel	δ T
3	0.39K
4	0.34

* Exclusive of errors from scattered sunlight (Section 3.11)

identical to the absolute thermodynamic temperature scale) is ± 0.10K. About half of this is the calibration accuracy; the remainder is produced by the sensor, bridge, and power supply. The latter produce errors that are largely random in nature, as do the readout device and temperature controller. The readout device introduces an error that can be kept small, about $\pm$ 0.01K for an integrating digital voltmeter. The stability of the controller is about $\pm$ 0.05K.

The base gradient or uniformity can be held to $\pm$ 0.10K. We have included this variation as part of the calibration error. In fact, the base temperature will be measured with an array of calibrated platinum sensors. The average of this array should then provide a measurement whose gradient error is less than the actual gradient. The gradient through the honeycomb can be estimated from the measurements on a similar target (A. R. Karoli, J. R. Rickey, and R. E. Nelson, Appl. Opt. 6, 1183, 1967). The honeycomb gradient was 1.6K in a 290K target that had a view factor of about 0.5 to a warm surround at 25°C. If the target temperature were reduced to 210K, the gradient would increase to about 2.5K. However, the view factor to the warm surround is reduced to 0.2 in our design, so the gradient is about 1.0K.

Moreover, the corresponding increase in the radiance temperature is much less than the gradient because most of the normal emission comes from the base and walls near the base. When the instrument views the calibration target at normal incidence during a calibration, the nominal cavity emissivity of 0.999327 (Section 7.1.2.2) may be divided between the base honeycomb and the cavity walls. For the nominal paint emissivity of 0.92, the base has a normal emissivity of 0.996696. Therefore 0.002631 of the normal cavity emissivity arises in the cavity walls (and is seen by reflection in the base). The emissivity of the base may, in turn, be divided among emission from the base bottom, the flat top area of the honeycomb, and the walls of the honeycomb. The fraction of flat area is 0.025, so that the emissivity from the top is 0.92 x 0.025 and from the bottom, 0.92 x 0.975. The remainder of base emissivity, 0.996 696 - 0.92 = 0.076 696 arises in the sides of the honeycomb. We will assume that the walls of the cavity emit at the bottom temperature of the base and that the base honeycomb sides have an exitance equal to the average of the basebottom and honeycomb flats. The effective exitance M_E of the target seen at normal incidence is then

$$0.999\ 327\ M_E = 0.061\ 348\ M_F + 0.937\ 979\ M_B,$$

where F denotes base flats and B base bottom. Now a calibration temperature will be the measured value of the base bottom B. In both Channels 3 and 4, we find that a honeycomb gradient $T_F - T_B = \pm$ 1K results in a calibration error $T_E - T_B = \pm$ 0.061K (see Table 7.1-6 in Section 7.1.2.2).

The temperature errors introduced by deviations in the cavity wall temperature were analyzed for Contract NAS5-21651 (HIRS for Nimbus F)*. This analysis shows that the wall temperature deviations (difference from the base and internal gradient) introduce a temperature uncertainty of only about $\pm$ 0.003K. As a result, the total temperature uncertainty in the chamber target is approximately 0.32K.

7.1.2.2 Deviation from a Blackbody

The uncertainties in the calibration of the instrument are expressed as absolute temperature errors in blackbody sources within the calibration range of each channel. The principles and practice of absolute radiometry are explored by R. E. Bedford and A. R. Karoli in Volume 14 of Advances in Geophysics (Precision Radiometry, ed. by A. J. Drummond, Academic Press, 1970). We have already covered the uncertainty in the temperature of the calibration target (Section 7.1.2.1). We now wish to consider the uncertainties produced by non-black calibration and cold space targets.

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* Memo from R. V. Annable "Deviations in the Wall Temperature of the Chamber Calibration Target", dated June 28, 1972.

The real problem here is not the small decrease in target emission below that of a blackbody, but the reflection of the higher temperature surround. The calibration target consists of a honeycomb array with a length to width ratio of 4:1 (or its emissivity equivalent in another geometrical form) housed in a tube whose length is equal to the aperture diameter (Figure 7.1-1). The tube is covered on its inner wall with a honeycomb array whose length to width ratio is 2:1. In this way, we obtain a second, large cavity in addition to the array of small cavities. It is also equivalent to controlling a large fraction of the target surround. The tubular enclosure must not be thermally attached to the base calibration target; this would induce significant thermal gradients in the target. In addition, the cavity mouth and base must be sufficiently large that only the base is seen by the instrument during a calibration.

Because a calibration depends on the difference in signals from the calibration and cold space targets, the accuracy can be further increased by making both targets in the same form and exposing them, as nearly as possible, to the same surround. We have an estimate of the residual non-black error based on a calibration target surround of 293K and a space target surround of 283K; it ranges from +0.018 to -0.046K in Channel 3 and from 0.027 to -0.016K in Channel 4.

The base of the calibration target is in the form of honeycomb cavity array in which the cavities have a length to width ratio of 4:1 (A. R. Karoli, J. R. Hickey, and R. E. Nelson, Appl. Opt. 6, 1183 (1967)). A single cavity may be approximated by a cylinder whose emissivity is given by (P. Campanaro and T. Ricolfi, J. Opt. Soc. Am. 57, 48 (1967)).

$$\varepsilon_c = \varepsilon + \left[\frac{\rho\alpha^2}{2}\left(1 + \frac{4}{\alpha^2}\right)^{\frac{1}{2}} - 1\right]$$

$$- \frac{\rho^2\ \alpha^2}{2}\left[\frac{1 + \frac{2}{\alpha^2}}{\left(1 + \frac{4}{\alpha^2}\right)^{\frac{1}{2}}} - 1\right]$$

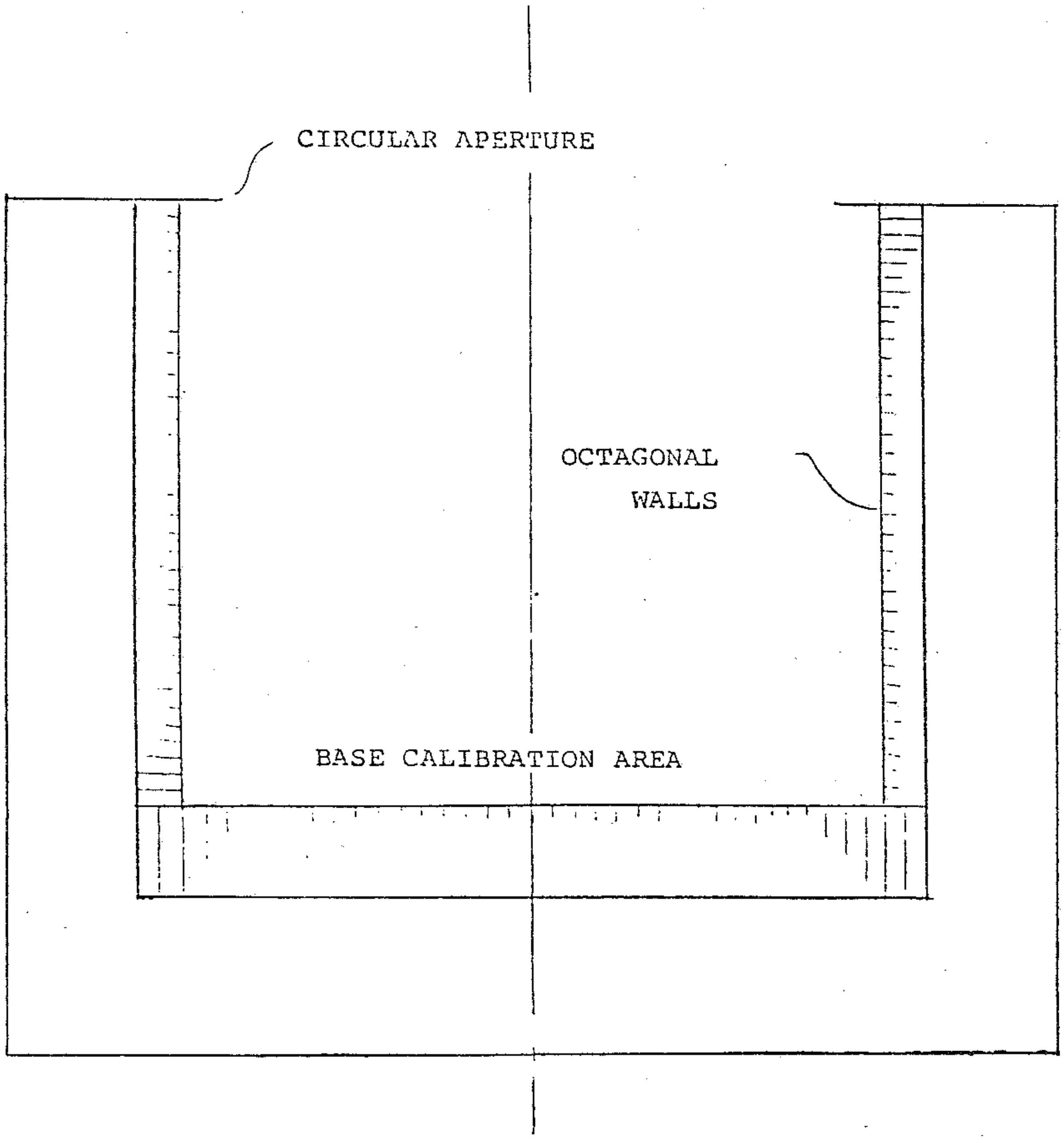

Figure 7.1-1 Chamber Calibration Target

where α = ratio of height to radius

ε = normal surface emissivity

ρ = hemispherical surface reflectivity.

For high emissivity materials, the normal and hemispherical emissivity are nearly equal (M. Jakob, Heat Transfer, Vol. I, Wiley 1949, Sections 4.9 and 7.2) and ρ is nearly equal to $(1 - \varepsilon)$.

The flat area of the array is about 2.5 percent of the total source area. The effective normal emissivity of the array is then

$$\varepsilon_A = 0.975\ \varepsilon_C + 0.025\ \varepsilon.$$

The formula of Companaro and Ricolfi for the normal emissivity of a cavity in the array can also be used to calculate the emissivity of the large cylinder (i.e., the complete target). The cavity array normal emissivity becomes the wall emissivity of the cylinder. To use the formula, we also need the hemispherical emissivity of the cavity array. This can be calculated from the limiting value formula of Treuenfels (J. Opt. Soc. Am. 53, 1162, 1963) or interpolated from the results of Sparrow and Cess (Radiation Heat Transfer, Brooks/Cole, 1966, pp. 164-165). However, when the cavity array normal emissivity and hemispherical reflectivity are used in the formula of Companaro and Ricolfi, we find that the normal emissivity of the cylinder exceeds unity even for an initial surface emissivity as low as 0.89.

To overcome this problem, we will use the formula developed by Bauer and Bischoff (Appl. Opt. 10, 2639, 1971). For a cylindrical cavity with a plane bottom perpendicular to the axis, they obtain a normal reflectivity of

$$\rho_C = \rho_O\ (1 - \rho_O)^{-1}\left[1 + (L/R)^2\right]^{-1} \qquad \text{Eq. (1)}$$

where ρ_O is the normal reflectivity of the inner surface and L/R is the length to radius ratio (α in the formula of Companaro and Ricolfi). According to the nomenclature developed by Nicodemus, et. al. (Appl. Opt. 9, 1474, 1970), ρ_O is the directional-hemispherical reflectance for normally incident flux, that is, the fraction of normally incident flux that is reflected into a hemisphere. It is also equal to the hemispherical-directional reflectance for normally incident flux, that is, the fraction of normally incident flux that is reflected into a hemisphere. It is also equal to the hemispherical-directional reflectance factor for normally reflected flux, that is, the fraction of hemispherically incident flux that is reflected in the normal direction.

Equation (1) is based on experimental measurements and holds for large value of α, the range of validity depending on the value of ρ_o. However, it yields a conservative result at all values of α, i.e., the calculated value of ρ_c is always greater than or equal to the experimental value. To begin with, we applied the equation to the cavity array in which 2.5 percent of the area is flat. The results are given in Table 7.1-4, where they are compared with those from the equation of Companaro and Ricolfi. We will assume the surface emissivity has a nominal value of 0.92.

The normal reflectivity ρ_N of the complete target can now be calculated from equation (1) by setting $\rho_o = 1 - \varepsilon_A$. The space in the chamber limits the value of the large cylinder to 2:1. The measurements of Bauer and Bischoff (op. cit.) show that the actual reflectivity will be less than that calculated from the formula because of the relatively low value of a. The results of the complete target are given in Table 7.1-5 at four values of the initial surface emissivity ε when the walls also have an L/R ratio of 8:1.

If we neglect multiple reflections between the wall and base of the cavity, we can write the cavity emissivity as

$$\varepsilon_N = \varepsilon_b + a\ \varepsilon_w,$$

where b = base, w = wall and a is a constant. For 4:1 cavities on both the base and wall, we have

$$a = \frac{\varepsilon}{\varepsilon_b} - 1 = 0.002\ 050$$

If the 4:1 honeycomb on the walls is replaced with 2:1, the wall emissivity is reduced to 0.993013. Using the same value of a,

Table 7.1-4. Normal Emissivity of the Honeycomb Cavity Array

ε Surface	ε_A B&B	ε_A C&R
0.89	0.99 6 396	0.99 5 451
0.91	0.99 6 266	0.99 6 304
0.92	0.99 6 696	0.99 6 726
0.93	0.99 7 121	0.99 7 145

Fraction of flat area = 0.025

L/R ratio of cavities = 8.

Table 7.1-5. Normal Reflectivity of In-Chamber Target With 4:1 Honeycomb Array on the Base and Walls

ε	ρ_N
0.89	0.000 925
0.91	0.000 750
0.92	0.000 663
0.93	0.000 577

the normal cavity emissivity is then reduced to

$$\varepsilon_N = 0.996\ 696 - 0.002650 \times 0.993013 - 0.999\ 327$$

Now the deviation of ε_N from unity produces an apparent change in the target radiance given by

$$\delta M = (1 - \varepsilon_N)\ (M_s - M_t)$$

where M is the blackbody exitance and the subscripts s and t denote surround and target, respectively. If the change in exitance is small, the corresponding change in effective blackbody temperature is given by

$$\delta T = \frac{\delta M}{dM/dT}$$

The values of M are given in Table 7.1-6 for Channels 3 and 4 at temperatures in the range from 185K (250K) to 321K. The values of δT at representative temperatures are as follows:

Channel	T	δT
3	185K	0.229K
3	320	-0.0164
4	250	0.0903
4	320	0.0118

Again a calibration depends on the difference between the calibration and space targets, and we can further reduce the non-black errors by constructing the targets in the same geometry and placing them in surrounds as identical as possible. In order to estimate the residual error after taking the difference between targets, we will assume that the calibration target has a surround at 293K and space targets a surround at 283K. The relative net error in terms of blackbody radiance is then

$$M_\lambda = \frac{3.7413 \times 10^4}{\lambda^5} \left[\exp\left(\frac{1.4388 \times 10^4}{\lambda T}\right) - 1\right]^{-1}$$

$$\delta^2 M = \varepsilon_N M_t + (1 - \varepsilon_N) M_{s1} - (1 - \varepsilon_N) M_{s2} - M_t$$

$$\delta^2 M = (1 - \varepsilon_N) (M_{s1} - M_{s2} - M_t)$$

where s1 denotes the surround of the calibration target and s2 the

Table 7.1-6 In-Band Radiant Exitance

	T (K)	(Emitted W cm^{-2})
Channel 3:	185	1.973×10^{-4}
	186	2.047×10^{-4}
	283	2.304×10^{-3}
	293	2.703×10^{-3}
	295	2.787×10^{-3}
	296	2.829×10^{-3}
	300	3.003×10^{-3}
	301	3.048×10^{-3}
	320	3.962×10^{-3}
	321	4.013×10^{-3}
Channel 4:	250	4.174×10^{-6}
	251	4.436×10^{-6}
	283	2.479×10^{-5}
	293	3.931×10^{-5}
	295	4.295×10^{-5}
	296	4.481×10^{-5}
	300	5.331×10^{-5}
	301	5.561×10^{-5}
	320	1.183×10^{-4}
	321	1.228×10^{-4}

Table 7.1-7 Net Non-Black Calibration Error

Channel	T	$\delta^2 T$
3	185K	0.0184 K
3	320	-0.0464
4	250	0.0266
4	320	-0.0156

surround of the cold space target. The corresponding errors in black body temperature are given in Table 7.1-7 for the representative temperatures.

7.1.2.3 Surround Difference Measurement

In order to verify that the space clamp target and calibration target are exposed to the same surrounds, it was suggested early in the AVHRR program that the two targets be switched in the chamber. This would show if surround reflections were contributing any error to one or the other target. A simpler check can be done by simply comparing the channel 4 signals when it views each target. When the calibration target is run to 175K, its exitance is below the noise level of the AVHRR in Channel 4. If the output of Channel 4 is then the same when viewing the cold space target, we can assume that the surrounds are not influencing the accuracy of the calibration in the thermal channels.

Table 7.1-8 shows the calibration data taken in channels 3 and 4 of the ETM on October 6, 1975. The baseplate temperature is $+30^{\circ}C$. The data shows that in channel 4, the output is identical when viewing the cold space target and the calibration target. As expected the channel 3 output shows some signal from the calibration target at 175K.

From this we conclude that there is no significant calibration error introduced into the thermal channels due to surround differences.

7.1.3 In-Flight Calibration Target

The in-flight calibration is provided by views of the internal blackbody at the housing temperature and of the zero level signal at deep space temperature.

7.1.3.1 Temperature Uncertainty

The temperature measurement error is $\pm$ 0.05K from the sensor calibration and $\pm$ 0.10K (specified value) from the instrumentations. Additional temperature uncertainties arise from the gradients within the internal target. The nominal gradient across the base of the

CHANNEL 3 OUTPUT			CHANNEL 4 OUTPUT	
Cal. Target Tamp.	Cal. Target Signal	Space Signal	Cal. Target Signal	Space Signal
K	mvolts	mvolts	mvolts	m volts
320	760.0	6187.5	931.2	6256.8
315	1112.8	6187.5	1879.0	6256.5
305	1769.3	6187.1	3357.1	6257.1
295	2349.6	6187.5	4325.6	6258.1
285	2878.4	6187.5	5035.	6257.1
275	3438.4	6188.1	5495.	6258.1
265	3893.4	6193.7	5822.8	6263.7
255	4284.3	6193.4	6007.1	6264.0
245	4636.2	6193.1	6123.4	6263.7
235	4960.3	6193.7	6189.3	6263.1
225	5225.0	6193.7	6230.0	6264.6
215	5450.6	6193.1	6247.5	6264.0
205	5641.2	6192.8	6254.0	6264.0
195				
185	5906.2	6193.4	6259.0	6263.1
175	5993.7	6193.7	6264.6	6264.6

TABLE 7.1-8 ETM AVHRR CALIBRATION RUN SHOWING SURROUNDS EFFECT

target is $\pm$ 0.08K, as determined by the thermal analysis of the instrument. The effective value of this gradient will again be reduced by using an array of calibrated platinum sensors to measure the base temperature. The worst case honeycomb gradient is 1.0K (DIR No. 18). Following an analysis similar to that given in Section 7.1.2.1, we find that the corresponding uncertainty in radiance temperature at normal incidence is 0.08K. The total temperature uncertainty of the internal inflight target is then 0.31K.

7.1.3.2 Deviation from a Blackbody

The internal target has a normal emissivity of 0.995 when coated with a black paint whose emissivity is 0.92. The deviation from a blackbody reduces the signal from the target itself but introduces an additional signal from the surround. To obtain the most accurate calibration of the internal target, we would have to compare its signal with that of the more accurate chamber target when the internal target is in the range of surrounds encountered in orbit. The worst case non-blackness errors is shown below to be about -0.08K in Channel 3 and -0.03K in Channel 4.

The internal calibration target is in the form of a honeycomb cavity array in which the length to width ratio is 4:1. Specifically, the basic material has a thickness of 0.001 inch and a cavity width (distance between flats) of 0.060 inch. Each cavity has two walls of its own (where the joined material has a double thickness) and four shared walls or a total of four. The ratio of flat to total target area is then

$$\frac{4\ A_w}{A_c + 4\ A_w}$$

where A_w is the top area of a wall and A_c the area of a cavity. If w is the distance between flats and t the thickness, we then have

$$A_w = \frac{t}{\sqrt{3}}\ (w - t)$$

$$A_c = 2\ \sqrt{3}\ (<1/2>w - t)^2$$

when the cavity openings are in the form of hexagons. For the above dimensions, the ratio of flat to total surface area is 0.045, and the normal emissivity is given by

$$\varepsilon_N = 0.045\ \varepsilon + 0.955\ \varepsilon_c$$

where ε is the emissivity of the black paint and ε_c the normal emissivity of the cavity.

The value of ε_c can be calculated from the formula of Bauer and Bischoff (Section 7.1.2.2). The results are listed in Table 7.1-9; the paint emissivity is 0.92.

In the case of the in-flight target, the non-black temperatuere error is given by

$$\delta T = \frac{\delta M}{dM/dT}$$

where $dM/dT = 4.263 \times 10^{-5}$ Wcm^{-2} K^{-1} in Channel 3 and 1.859×10^{-6} Wcm^{-2} K^{-1} in Channel 4 for a target at T = 295K. The apparent change in target radiance δM is given by

$$\delta M = (1 - \varepsilon_N)\ F_{te}\ M_e - (1 - F_{ti})\ M_t$$

where
F_{te} = view factor from target to earth = 0.21
F_{ti} = view factor from target to instrument = 0.741
M_e = infrared exitance of earth
M_t = infrared exitance of the target and instrument.

The view factors are taken from the thermal analysis of the instrument; they are the values when the instrument is viewing the internal target. As a worst case, then we will assume the earth is at its minimum temperature of 185K.* Using the exitance values from Table 7.1-6 and the target emissivity of 0.995 122, we obtain

$$\delta T\ (\text{Channel 3}) = -0.080\text{K}$$
$$\delta T\ (\text{Channel 4}) = -0.029\text{K}$$

for the non-blackness errors in the inflight calibration at T = 295K.

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* The corresponding exitance in Channel 4 is 1.944×10^{-8} Wcm^{-2}.

Table 7.1-9 Normal Emissivities of the Internal Inflight Calibration Target

ε	ε_c	ε_N
0.89	0.998 099	0.994 584
0.91	0.998 478	0.994 947
0.92	0.998 662	0.995 122
0.93	0.998 842	0.995 294